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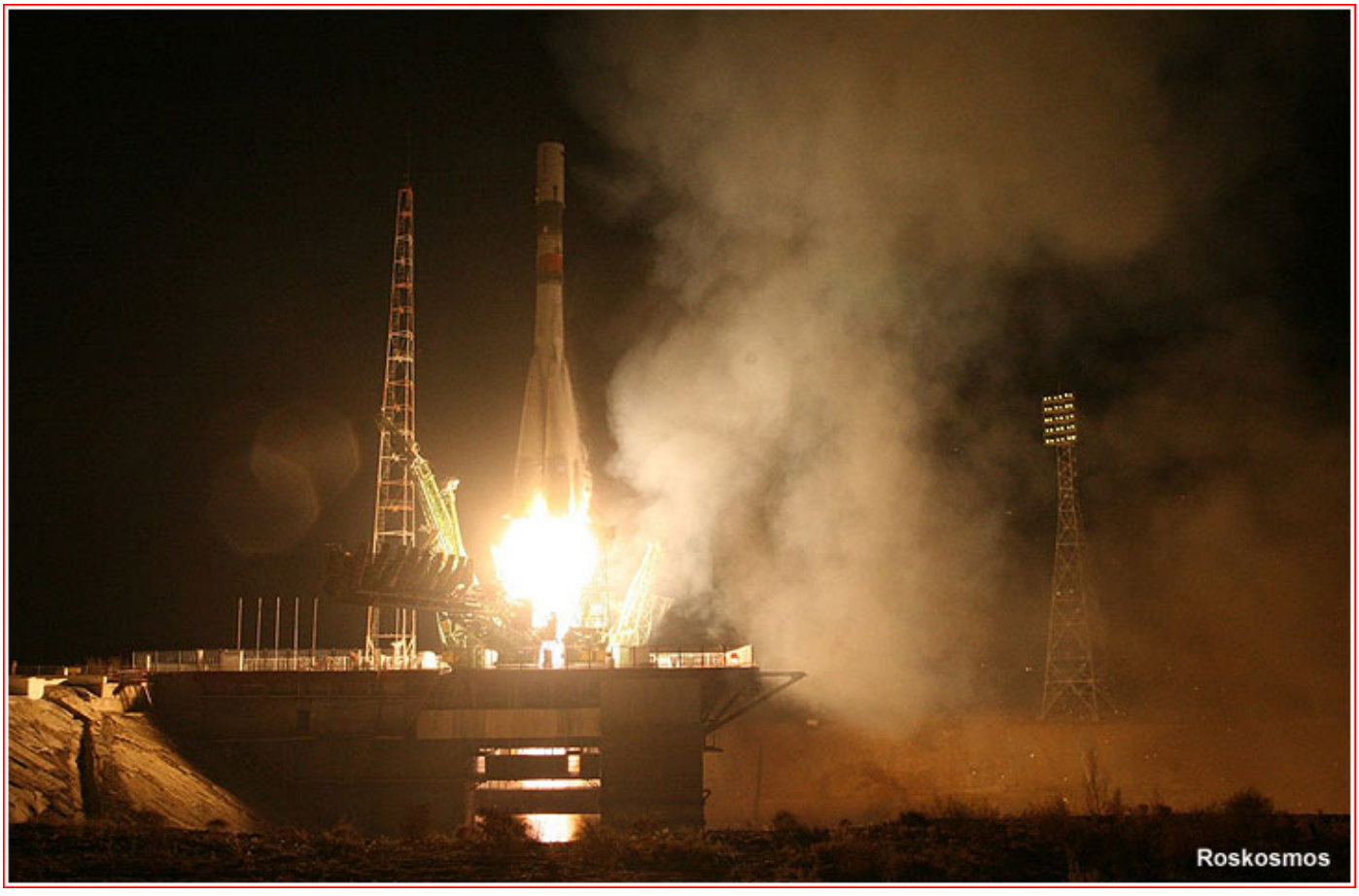
A fresh cargo ship lifted off from Baikonur on Dec. 1, 2016, heading to the International Space Station, ISS. However six minutes after the liftoff, telemetry stopped coming from the mission during the powered flight of the third stage of the Soyuz-U launch vehicle.

Previous Progress mission: Progress MS-03



A Soyuz-U rocket with Progress MS-04 lifts off on its ill-fated mission on

Dec. 1, 2016.

Progress MS-04 mission at a glance:

Spacecraft	Progress MS-04 (No. 434)
Launch vehicle	Soyuz-U
Launch site	Baikonur, Site 1, Pad 5
Mission	Unmanned cargo delivery to the ISS
Spacecraft mass	7,290 kilograms
Total cargo mass	2,442 kilograms
Launch date and time	2016 Dec. 1, 17:51:52.474 Moscow Time (actual)
Accident time and altitude	L+382.3 seconds at 181 kilometers during the operation of the third stage
Docking date and time	2016 Dec. 3, 19:43:06 Moscow Time (planned)
Destination	Docking at ISS (aft port on the Zvezda Service Module)

Progress MS04 was scheduled to deliver supplies for the 50th long-duration expedition on the station. In the ISS flight manifest, the Progress MS-04 spacecraft had the designation 65P, denoting the 65th Russian cargo mission heading to the outpost, while in production documentation it was designated No. 434.

Launch vehicle dilemma mars preparations for Progress MS-04 launch

The Progress MS-04 was launched into orbit on the second to last Soyuz-U

rocket before the switch to a new-generation Soyuz-2 family, which did not depend on avionics produced in Ukraine. This move to the new variant acquired a new political significance after the Kremlin's confrontation with Kiev in 2014. However, inside the Russian space industry, this move became controversial after the loss of the Progress M-27M spacecraft on April 28, 2015, which was blamed on design features specific to the third stage of the Soyuz-2 rocket. Although the Soyuz-2 was officially declared fully operational in March 2016, there was lingering concern over this variant's reliability in the long term, stressing the need for a potential backup. The rocket issue remained open as the Progress MS-04 launch campaign got underway.

The mission of Progress MS-04 was previously scheduled for July 1, 2016, but it later slipped back, along with the rest of the ISS flight manifest. Following the lengthy delay with the launch of the Soyuz MS-02 mission in September 2016, the liftoff of Progress MS-04 was rescheduled from October 20, at 10:40 Moscow Time to Dec. 1, 2016.

The fueled Progress MS-04 spacecraft is installed into its access rig inside processing building at Site 254 on Nov. 22, 2016.

The final phase of the launch campaign for Progress MS-04 began on Nov. 17, 2016, when mission management cleared the spacecraft for fueling. The operation included the loading of propellant into the ship's own propulsion system, KDU, and into the tanker section designed for refueling of the Zvezda Service Module in orbit. The fueling was completed by November 22, when the spacecraft was returned to the processing building at Site 254 in Baikonur. On November 24, the Progress was integrated with its launch vehicle adapter and a day later, engineers from RKK Energia, which built the ship, conducted the traditional final inspection of the spacecraft, before it was

rolled inside its payload fairing.

On November 27, the payload section was transferred from the processing facility at Site 254 to the vehicle assembly building at Site 112 for integration with the launch vehicle. In the next 24 hours, the payload section was integrated with the third stage of the launch vehicle and the resulting upper composite was connected to the booster stages of the Soyuz-U rocket. Upon the completion of the assembly, mission officials approved the rollout of the launch vehicle to the launch pad next morning.

A Soyuz-U rocket with Progress MS-04 shortly after arrival at launch pad No. 5 at Site 1 in Baikonur.

Progress MS-04 was to follow a two-day rendezvous profile

The Progress MS-04 was expected to enter its initial parking orbit with the

following parameters:

Parameter	Planned orbit
Orbital period	88.59 minutes (+/-0.37 minutes)
Inclination	51.66 degrees (+/-0.06 degrees)
Perigee	193 kilometers (+7/-15 kilometers)
Apogee	245 kilometers (+/-42 kilometers)

At the time, the ISS was projected to be in a 404.89 by 419.26-kilometer orbit, 288.9 degrees away from the cargo ship in the so-called phasing angle. Without any additional maneuvers, the spacecraft would remain in orbit for around 30 hours or 20 revolutions around the Earth.

The Progress MS-04 mission was to use the two-day, 34-orbit trip to the station instead of the previously available six-hour rendezvous profile.

During the long-range rendezvous process, the cargo ship would conduct a dual maneuver on December 1, during the third orbit of the mission, to enter the prescribed phasing orbit with the station and a single orbit correction was to be performed on December 2, before the autonomous rendezvous process could begin. The maneuvers were to be initiated according to the following timeline and had to result in the following orbital parameters:

Orbit No.	Time	Firing duration	delta V	Period	Inclination	Resulting perigee	Resu apo
Day 1 of the mission (Dec. 1, 2016)							
3	21:14:39	63.1 seconds	25.04 m/s	89.44 minutes	51.66 degrees	200.5 kilometers	314.8 kilom
3	21:53:43	68.9 seconds	21.90 m/s	90.40 minutes	51.66 degrees	292.9 kilometers	317.8 kilom
Day 2 of the mission (Dec. 2, 2016)							

17	18:59:45	29.2 seconds	2.00 m/s	90.47 minutes	51.66 degrees	298.8 kilometers	318.0 kilom

The autonomous rendezvous process between the spacecraft and the station was to be initiated on Dec. 3, 2016, at 17:18:23 Moscow Time (9:18 a.m. EDT). Final maneuvers, including flyaround of the station, station-keeping and berthing were scheduled to commence at 19:19:00 Moscow Time on (11:19 a.m. EDT).

According to the flight schedule, Progress MS-04 was scheduled to dock at the aft port of the Zvezda Service Module, SM, a part of the Russian segment of the ISS on Dec. 3, 2016, at 19:43:06 Moscow Time (11:43 a.m. EDT), during 34th orbit of the cargo mission. The nominal docking was expected to be fully automated with Russian cosmonauts Sergei Ryzhikov and Oleg Novitsky on stand-by inside the station, ready to engage manual remote-control if needed.

Progress carried significant cargo to ISS

Along with its nearly 2.5 tons of routine cargo, Progress MS-04 carried a number of significant items, including the upgraded Orlan-MKS spacesuit for Russian spacewalks, a mini-greenhouse and an experimental system to recycle water and urine, the official Russian *TASS* news agency reported.

The Lada-2 greenhouse experiment was to continue a long-term studies of plants in weightlessness, which began on the Soviet Salyut space stations and then continued on Mir with the Svet greenhouse and with the first Lada experiment on the Russian segment of the ISS.

The SRV-U-RS water and urine recycling system developed at Moscow-based NII Khimmash institute was to be installed in the MIM1 Rassvet module and

would be used within the Separatsiya (separation) experiment.

Progress MS-04 also carried equipment for the Probiovit experiment, which was to test a method to produce "pro-biotic" drinks, such as the Russian traditional fermented milk product known as kefir. The immune system-strengthening kefir could be consumed on lunar bases and during expeditions to Mars to improve the bacterial environment in the digestive system of future space travelers, Russian researchers believe.

Cargo aboard Progress MS-04:

Total spacecraft liftoff mass	7,285 kilograms
Propellant for the integrated propulsion system, KDU	880 kilograms
Propellant in the refueling tanks	710 kilograms
Oxygen in the Oxygen Supply System, SrPK	52 kilograms
Water in the Rodnik system	420 kilograms
Total mass of supplies in the pressurized cargo compartment, including...	1,260 kilograms
> Gas Content System, SOGs (absorbent P-16, gas-analyser equipment, air-purification system hardware)	67 kilograms
> Water Supply System, SVO (filter-divider membrane, purification column unit, water container, supplies for the Rodnik system)	253 kilograms
> Sanitary and Hygiene Supplies, SGO (toilet system inserts, toilet paper, solid waste container, separator pump, trash container, toilet system supplies)	83 kilograms
> Medical Supplies, SMO (medical checkup equipment, personal hygiene items, means of anti-weightlessness effects prevention,	115

first-aid equipment, air-monitoring equipment, cleaning supplies)	kilograms
Food Provisions, SOP, (containers with food, fresh food items, napkins, food disposal bags)	315 kilograms
Personal Protection Equipment, SIZ, (Orlan-MKS spacesuit)	98 kilograms
Thermal Control System, SOTR (dust filter replacement cartridges, replacement unites, ventilators)	32 kilograms
Onboard Equipment Control System, SUBA, (power commutating units)	3 kilograms
Onboard Measurement System, SBI, (cable kit)	1 kilograms
Power Supply System, SEP (cable kit)	6 kilograms
Telephone and Telegraph Communications System, STGS (equipment)	1 kilograms
Servicing and Repair System, STOR (electric drill set, container bags, instrument kit and supplies)	16 kilograms
Means of Crew Support, KSPE (photo-equipment, personal packages for the crew, onboard documentation, souvenirs)	25 kilograms
Instrument payloads, KTsN (medical and life-science experiments: KE Pilot-T, KE Rasteniya-2; biotechnology: KE Konstanta-2, KE Aseptik, KE Probiovit, KE Kulonovsky Kristall)	18 kilograms
	140 kilograms
American cargo (cargo for US crew members, life-support items, water-recycling hardware etc.)	87 kilograms
Total mass of cargo	**2,442 kilograms**

Anomaly during the launch

The Soyuz-U rocket carrying the 7,290-kilogram Progress MS-04 cargo ship lifted off from Pad 6 at Site 31 in Baikonur on Dec. 1, 2016, at 17:51:52.474 Moscow Time (9:51 a.m. EDT).

Following a vertical liftoff, the launch vehicle headed eastward from Baikonur matching an orbital inclination of 51.66 degrees toward the Equator. The four boosters of the first stage separated nearly two minutes into the flight, while the second stage continued firing until 4.7 minutes into the flight.

The third stage ignited moments before the separation of the second stage, firing through a lattice structure connecting the two boosters and ensuring continuous thrust during the entire ascent to orbit.

Less than 10 seconds after the separation of the second stage, the payload fairing protecting the spacecraft split into two halves and fell off. A fraction of a second later, the aft cylindrical section of the third stage split into three segments and dropped off, ensuring the fall of all the debris into the same drop zone 1,576 kilometers from the launch site.

The third stage was scheduled to continue firing until almost nine minutes into the flight, however six minutes into the ascent, mission control detected loss of telemetry from the vehicle. Live TV broadcast from Roskosmos continued, however the usual report confirming the separation of the third stage never came.

Shortly after the planned separation around nine minutes into the flight, NASA quoted Russian mission control as confirming the deployment of navigation antennas, but not solar arrays, on the Progress MS-04. Shortly thereafter, Roskosmos confirmed that telemetry from the mission had been

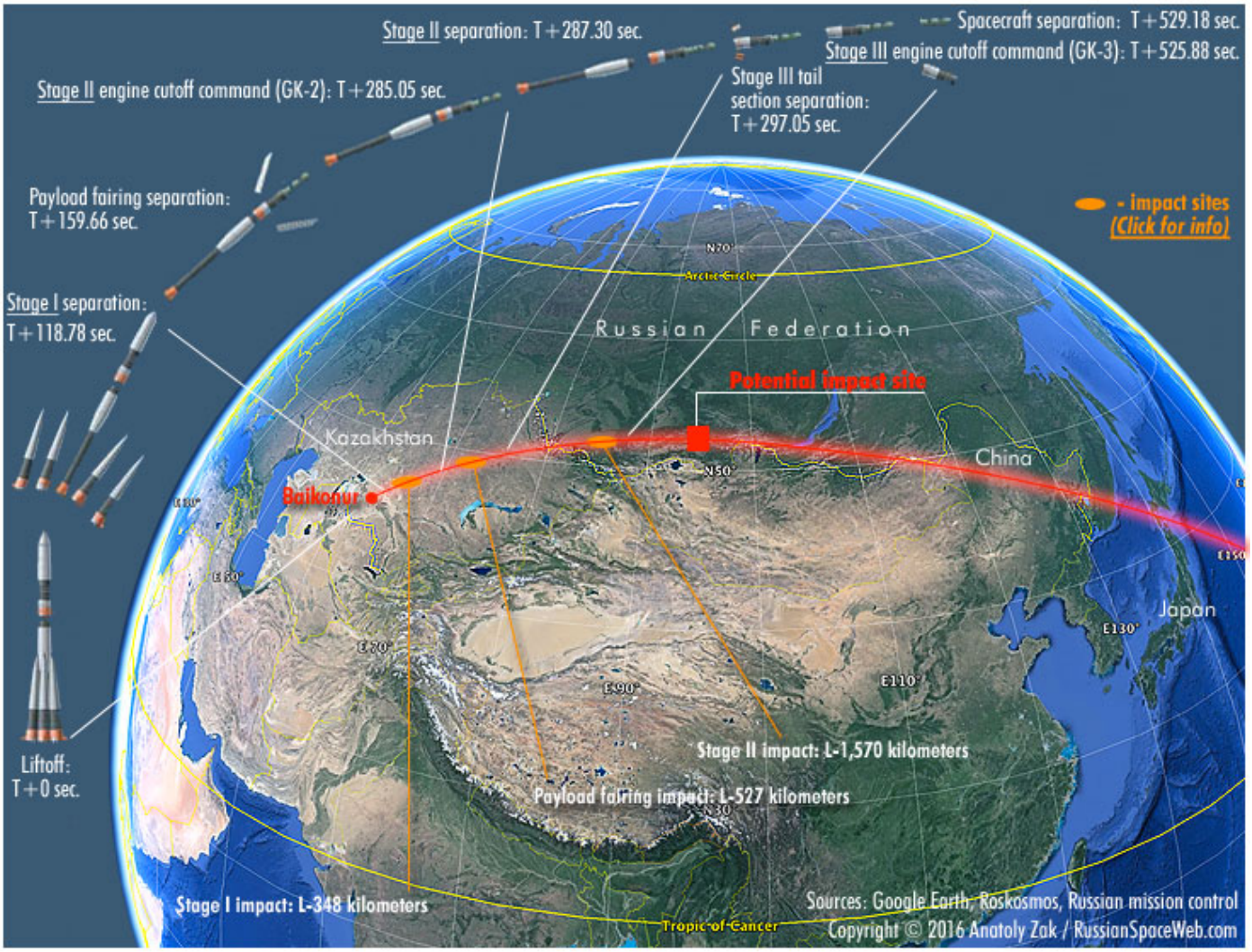
interrupted at L+383 seconds. Both agencies had no information on the fate of the spacecraft.

In the meantime, a large explosion in the sky over the Tuva Region of Russia was observed, followed by reports of ground shaking and falling debris.

At 20:39 Moscow Time, Roskosmos announced that its tracking facilities had not detected Progress MS-04 in its planned orbit. According to preliminary details, the anomaly leading to the loss of the spacecraft took place at an altitude of 190 kilometers over the sparsely populated and rugged terrain of the Tuva Republic and most of the ship's fragments burned up in the upper atmosphere, Roskosmos said.

According to Roskosmos, a State Commission was analyzing the situation, however the loss of the spacecraft would not affect normal operation of the ISS and the life of its crew.

On December 3, Roskosmos said that the Soyuz-U rocket with the Progress MS-04 spacecraft was insured for 2,135 billion rubles through VTB Strakhovanie. The State Corporation also said that the Interagency Commission led by Roskosmos Head Igor Komarov and his Deputy Aleksandr Ivanov was scheduled to complete the investigation by December 20, 2016.



Progress MS-04 crashes in Southern Russia

Four hours after the failed launch, Russian media reported that the crash site had been located in the heavily wooded area of the Choisky District in the Tuva Republic, around 40 kilometers from the nearest residential area. The site was reportedly secured, but the arrival of space officials to this remote area by helicopter was hampered by bad weather.

On the morning of December 2, the *RIA Novosti* news agency reported that the impact site had been located from 60 to 70 kilometers west of town of Kyzyl in the Tuva Region. One piece of debris was reported 120 kilometers west of Kyzyl.

On December 3, residents in the Ulug-Khemsky District found a 0.9-meter tank attributed to the Progress MS-04 in the settlement of Tos-Tevek, 15 kilometers from the village of Eilig-Khem.

The investigation begins into the Progress MS-04 launch failure

Based on the preliminary analysis of the accident, all transmissions from the BR-92R-7M telemetry system on the Soyuz-U rocket ceased abruptly at L+382.3 seconds in flight at an altitude of 181 kilometers, *RIA Novosti* reported. No issues with the flight had been detected until that moment. During the ascent, all the telemetry from the rocket and from the spacecraft is transmitted to ground stations via antennas installed in the intertank compartment, MBO, of the third stage.

According to an unconfirmed report on the online forum of the *Novosti Kosmonavtiki* magazine, at the time of the accident, the rocket's flight control system issued the so-called AVD command, which stands for the "Emergency Engine Cutoff." The AVD command was reportedly triggered during the interval between L+382.31 and 382.37 seconds by an unacceptable deviation of the vehicle from its prescribed trajectory, which was so severe that it had caused the rocket's gyroscopic control system to stall. Moreover, the cargo ship was apparently sheared off from the stage shortly thereafter in a violent breakup, followed by a some sort of impact between the two vehicles.

Overall, this account resembled the circumstances leading to the loss of the Progress M-27M spacecraft in April 2015.

This version of events was apparently discussed within 24 hours after the accident at a meeting of the top managers at KB Khimavtomatiki design bureau. The company, based in the city of Voronezh, developed the RD-0110 engine for the third stage of the Soyuz-U launch vehicle.

At the same time, other interpretations of the data disputed this description, claiming that the separation looked normal because the spacecraft followed the prescribed trajectory after the accident. This account also said that the spacecraft had remained in a stable flight after its premature split from the

rocket, however there was also data about a gradual fall of pressure in the instrument compartment and in the thermal control system of the Progress. This type of event could be caused by an impact, as well as by an anomaly in the spacecraft itself or could be related to the reentry and breakup of the spacecraft in the atmosphere. What exactly initiated the separation command remained unclear as of December 3.

Another reliable source on the same forum reported that the AVD command can be issued based on only two criteria: the vehicle deviating from its correct orientation in space more than allowed or the fall of pressure in the combustion chamber of the engine. None of these criteria had been violated as late as L+382.314 seconds, the source claimed.

The reports from NASA, quoting Russian sources, about the deployment of navigation antennas on the doomed cargo ship could indicate the separation of the spacecraft and the rocket stage after the engine cutoff. However due to lack of orbital velocity at the time of the accident, Progress had no chance of reaching orbit. According to the *TASS* news agency, quoting a spokesman of the Central Military District, the radar of the Russian Anti-Aircraft Defense Forces, PVO, tracked two objects at 17:56 and 17:57 Moscow Time, exactly when the Progress MS-04 mission was underway.

According to some reports, telemetry from the Progress MS-04 was received at the NIP-7 Klyuchi ground station near the town of Barnaul.

The uncertainty surrounding the accident led to a blame game in the Russian media between industry sources representing the launch vehicle manufacturer on one side and the spacecraft developer on the other.

Investigators piece together circumstances of the Progress crash

Ten days after the loss of the Progress MS-04 spacecraft, the root cause of the

accident largely remained a mystery to the investigators, but a number of posts from industry sources on the online forum of the *Novosti Kosmonavtiki* magazine shed a great deal of light on the circumstances surrounding the unexplained launch failure.

Based on the telemetry leading to the accident, investigators established that the launch vehicle most likely had never received the so-called AVD command for the emergency engine cutoff, despite previous reports that such a command had been issued. Nevertheless, it became clear that the spacecraft and the third stage of the Soyuz-U launch vehicle had separated around 140 seconds prematurely during the powered ascent to orbit. The cause of the separation still remains a mystery, but engineers were apparently checking the hypothesis that the flight control system onboard the cargo ship could initiate the process. Under normal conditions, pyrotechnics cut links between the two vehicles on a command from the rocket after it has reached orbit. However, the spacecraft has its own backup process, which could perform the same operation. Observers were especially puzzled by the fact that the physical separation between the two vehicles was even possible at all, with the third stage still accelerating under the full thrust of its RD-0110 engine.

What is certain is that computers on Progress MS-04 interpreted the separation as nominal and initiated a sequence, which would be normally performed upon reaching orbit, including the deployment of the ship's antennas and the preparation of the attitude control thrusters, DPO, for action. However, moments after the separation, the spacecraft appeared to be struck twice by the rocket stage, which clearly continued its powered flight. The first impact came nearly straight into the aft bulkhead of the ship, then the second hit landed moments later into the side of the vehicle.

The collision apparently caused the spacecraft's propulsion system, SKD, to shift to the side from its normal position, the temperature inside its enclosure

to plummet and the whole vehicle to tumble. The telemetry from the Progress also indicated the activation of its thermal control system, probably in response to a breach in the ship's transfer compartment.

At the same time, there were conflicting interpretations of the telemetry coming from the rocket around the same period of time, with some sources claiming it to be normal, while others admitting that the timing of its registered milestones did not match those of the spacecraft and indicating an abnormal separation from the spacecraft.

Engineers were reportedly evaluating fragments of telemetry, which come from the rocket after the separation, even though most of such data was apparently cut very abruptly, which is another major puzzle facing the investigators, because the telemetry usually reveals plenty of warning signs about an impending failure. One hypothesis explaining the very sudden loss of data considered damage to the telemetry antenna on the rocket stage as a result of a secondary collision with the spacecraft.

Progress MS-04 accident timeline as of Dec. 19, 2016:

Elapsed time, sec.	Moscow Time	Launch vehicle	Cargo ship	Notes
286	17:56:40	GK-2 command (Stage 2 separation)	DPO thruster pipelines begin vacuuming	-
345-360	17:57:45-17:57:50	The OP pressure parameter increase observed. All is nominal	Pressure increase in the DMT21 thermal control line observed; DMT11 line shows no change. All is	Pressure in thermal control lines, DMT21, emulates OP parameters (in pressure table).

			nominal	
382.2*	17:58:14	Telemetry interference. Emergency engine cutoff command, AVDU, is suspected.	Telemetry interference	From GK2 command until the PO command (orbit confirmation), the AVDU command can be issued based on gyro deviation axis on the 3rd stage of the launch vehicle. It does not generate the spacecraft separation command, KO, or sends any other signals to the cargo ship's control system.
382.4*	17:58:14.2	Complete interruption of telemetry	Separation contact closure received	Cargo ship's control system initiates the preparation of the ship's propulsion system, KDU, for operation.
384**	17:59:16	-	Telemetry interruption ends, normal reception resumes. Decrease in parameters is observed in DMT11 and DMT211. Tank pressurization, filling of propellant lines with fuel and oxidizer. The spacecraft separates from the launch vehicle.	The DMT11 pressure fall coincides with the initial interruption of telemetry from launch vehicle and spacecraft. Fall of DMT21 confirms the 11D55 engine cutoff. Fall of pressure in DMT11 indicates a breach in the Thermal Control System loop No. 1 of the cargo ship. Based on pressure increase, the activation of the cargo ship's systems starts at T+382.4 seconds.
			Pressurization of the cargo	

-	17:59:16-17:59:30	-	ship's propellant tanks is completed.	-
-	17:59:30-17:59:50	-	Pressure readings are not decreasing	-
-	17:59:50	-	Complete loss of telemetry from the cargo ship	-

**Accuracy from 0.1 to 0.2 seconds; **384 seconds does not match 17:59:16 Moscow Time*

Investigators suspect oxygen tank rupture in the Progress MS-04 accident, manned missions grounded.

Throughout December 2016, engineers were still working on determining the root cause of the Progress MS-04 accident and toward the end of the month, Roskosmos had to extend the investigation until December 30 and then to Jan. 9, 2017.

By that time, experts apparently began leaning toward a theory about some kind of structural failure in the oxidizer tank of the third stage, but some improbable assumptions had to be made in order to explain the phenomenon, which could lead to an accident under the known circumstances.

On December 28, the *Govorit Moksva* radio-station cited two possible failure scenarios, quoting a source in the State Commission investigating the accident.

According to one theory some unforeseen dynamic loads on the tank's

structure were exacerbated by low-quality welding of the tank and led to its rupture.

Another hypothesis presumed that an anomalous operation of the RD-0110 engine, (as a result of higher-than-normal vibrations in its bearings or in its turbopump), could apply unforeseen loads onto the aft bulkhead of the oxidizer tank, which is located right above the engine.

Both scenarios were based on theoretical assumptions and could not be proven without doubt due to lack of telemetry.

By December 28, the *Interfax* news agency reported that the third stage of the remaining Soyuz-U rocket had been shipped from the Baikonur launch site back to its manufacturing plant in the city of Samara for further evaluation. There were also reports that the Progress MS-05 cargo mission to the ISS, previously planned for launch on Feb. 21, 2017, could be switched from the Soyuz-U to the newer Soyuz-2-1a rocket. However, the circumstances of the latest accident could also undermine confidence in the reliability of the Soyuz-2-1a rocket as well, because it had previously been involved in a similar accident.

Progress MS-04 failure investigation ends

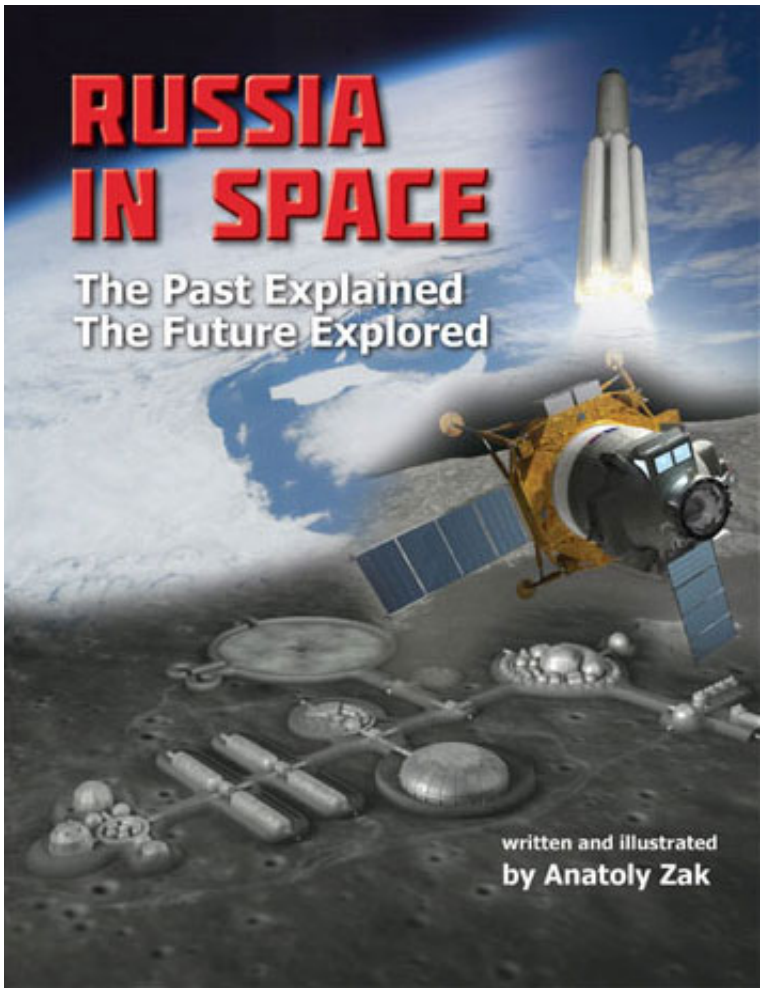
On Jan. 11, 2017, the investigation commission chaired by Director General of the Roskosmos State Corporation Igor Komarov reviewed the results of the investigative work into the Progress MS-04 accident.

According to Roskosmos, the accident led to the unplanned separation between the third stage of the launch vehicle and the spacecraft. Members of the commission established that the most probable cause of the accident had been the disintegration of the oxidizer tank of the third stage as a result of the failure of the 11D55 engine, following the fire and disintegration of its oxidizer

pump, Roskosmos said. The fire in the pump and its disintegration could be triggered by a possible injection of the foreign particles into the pump's cavity or by violations during the assembly of the 11D55 engine, such as a wrong clearance between the pump's shaft and its attachment sleeve, floating rings and impellers, leading to a possible loss of balance and vibration of the rotor.

The fault, which has a production nature, manifested itself during the flight, Roskosmos said. The State Corporation promised to prepare a plan of immediate action at enterprises of the the rocket industry to ensure the safe launch of the Progress MS-05 spacecraft, Roskosmos announced.

Read much more about the history of the Russian space program in a richly illustrated, large-format glossy edition:



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